

PATENT APPLICATION TRANSMITTAL LETTER

(Large Entity)

Docket No.
INTL-0277-US (P7626)

TO THE ASSISTANT COMMISSIONER FOR PATENTS

Transmitted herewith for filing under 35 U.S.C. 111 and 37 C.F.R. 1.53 is the patent application of:

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For: DISCRETE FILTER

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- ☒ Certificate of Mailing with Express Mail Mailing Label No. EL515088625US
- ☒ 3 sheets of drawings.
- ☐ A certified copy of a application.
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Multiple Dependent Claims (check if applicable) <input type="checkbox"/>					\$0.00
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**APPLICATION
FOR
UNITED STATES LETTERS PATENT**

TITLE: DISCRETE FILTER

APPLICANT: TINKU ACHARYA

Express Mail No.: EL515088625US

Date: November 2, 1999

DISCRETE FILTER

BACKGROUND

The invention generally relates to a discrete filter.

Electronic filters may be used in a wide range of applications. As examples, filters may be used in digital imaging applications to filter out noise, and filters may be used in wireless communication applications to reduce inter-symbol interference and aliasing effects. One general type of filter is a discrete, or digital filter, that may form the basis of most digital signal processing (DSP) operations.

The digital filter may be a finite impulse response (FIR) filter, a filter in which the impulse response of the filter is zero outside of a predefined interval; or an infinite impulse response filter (IIR), a filter in which the impulse response of the filter does not fall to zero outside of a predefined interval. As an example, the FIR filter receives indications of sampled values (called $x(i)$) of an input signal to produce digitized values (called $y(i)$) of the filtered output signal, as described by the following equation:

$$y(i) = \sum_{j=-N}^N C(j) \cdot x(i+j) = C(0) \cdot x(i) + \sum_{i=1}^N \{C(j) \cdot x(i+j) + C(-j) \cdot x(i-j)\}, \quad \text{Eq. (1)}$$

where “ $C(j)$ ” represents a particular filter coefficient and “ j ” denotes the index value used in the summation. The number of coefficients ($2N+1$) in Eq. 1 equals the number of taps of the filter. The filter may be further classified as being symmetric or asymmetric. For a symmetric filter, the $C(j)$ coefficients are symmetric about $j=0$. Thus, $C(-n)=C(n)$ for a symmetric filter. Otherwise, the filter is asymmetric.

A conventional filter may use a general purpose DSP processor to perform the summation described by Eq. 1 to derive each $y(i)$ value. In this manner, the DSP processor may include a multiplier-accumulator (MAC) unit that uses a multiple number of processing clock cycles (one for each multiplication, for example) to derive each $y(i)$ value. Unfortunately, the processing time of this arrangement may be too long for some applications. Alternatively, an arrangement called a tapped delay line may be used to produce the $y(i)$ values. The tapped delay line includes serially coupled processing stages, and each processing stage is associated with one of the $C(j)$ coefficients. Unfortunately, a conventional tapped delay line is specifically designed for a specific number of taps, a feature that limits the number of filter designs that may use this delay

line. Furthermore, due to its size, the tapped delay line may occupy a large semiconductor area and may consume a considerable amount of power.

Thus, there is a continuing need for an arrangement that addresses one or more of the problems that are stated above.

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SUMMARY

In one embodiment of the invention, a digital signal processing circuit includes a processing chain that has a selectable number of taps and a tap selection circuit. The tap selection circuit is coupled to the processing chain to establish the number of taps of the chain.

10 Advantages and other features of the invention will become apparent from the following description, drawing and claims.

BRIEF DESCRIPTION OF THE DRAWING

15 Fig. 1 is a schematic diagram of a digital filter system according to an embodiment of the invention.

Fig. 2 is a schematic diagram of the processing chain of Fig. 1 according to an embodiment of the invention.

Fig. 3 is a schematic diagram of a processing unit of the chain of Fig. 2 according to an embodiment of the invention.

20 Fig. 4 is a more detailed schematic diagram of the digital filter system of Fig. 1 according to an embodiment of the invention.

Fig. 5 is a schematic diagram of a unit that may be replicated to form a processing chain according to another embodiment of the invention.

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DETAILED DESCRIPTION

Referring to Fig. 1, an embodiment 5 of a digital filter system in accordance with the invention includes a systolic processing chain 10 that has a selectable number of taps. Due to this architecture, the system 5 may be used to form a wide range of digital filters, as the number of taps may be selected by a programmable tap selection circuit 12 that is coupled to the processing chain 10. As further described below, output terminals 11 of the processing chain 10

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may indicate a filtered output value (called $y(i)$) on each cycle of a clock signal (called CLK_1), a feature that results in 100% throughput for the processing chain 10.

As an example, in some embodiments, the digital filter system 5 may be used to implement a symmetric finite impulse response (FIR) filter. Due to the symmetry ($C(n) = C(-n)$) of the filter coefficients for this type of filter, Eq. 1 may be simplified, as described by the following equation:

$$y(i) = C(0) \cdot x(i) + \sum_{j=1}^N C(j) \cdot (x(i-j) + x(i+j)) \quad \text{Eq. (2)}$$

In Eq. 2, each “ $x()$ ” denotes a particular input value, “ $C()$ ” represents a particular filter coefficient and “ $y(i)$ ” represents a particular filter output. It may be noted from Eq. 2 that although the number of taps of the filter is $2N+1$, the number of filter coefficients (i.e., $C(0)$, $C(1)$, $C(2)$, . . . $C(N)$) that are used by the filter is equal to $N+1$. Thus, except for the $C(0)$ filter coefficient (that is associated with one tap of the filter), each $C(j)$ filter coefficient is associated with two taps of the filter due to the symmetry. For example, N equals three for a seven tap filter, and as an example, a particular output value $y(10)$ for the seven tap filter may be described by the following equation:

$$y(10) = C(3) \cdot \{x(9) + x(13)\} + C(2) \cdot \{x(8) + x(12)\} + C(1) \cdot \{x(9) + x(11)\} + C(0) \cdot x(10) \quad \text{Eq. (3)}$$

Thus, except for the $C(0)$ coefficient, each $C(j)$ coefficient is multiplied by a pair of input values (i.e., $x(i-j) + x(i+j)$). Referring to Fig. 2, in some embodiments, these multiplications may be performed by $N+1$ processing units 20 (processing units $20_0, 20_1, \dots, 20_k, \dots, 20_{n-1}, 20_n$, as examples) of the chain 10, each of which exploits the symmetric property of the filter by multiplying a different $C(j)$ coefficient by the appropriate pair of input values. As further described below, the processing units 20 form a systolic architecture, an architecture in which all of the processing units 20 are producing products on each clock cycle of the CLK_1 signal so that the chain 10 produces a different output value on each clock cycle.

More particularly, the processing units 20 are serially coupled together to form a serial chain for forming the output values, a chain in which the processing occurs from the processing unit 20_n to the processing unit 20_0 . Each processing unit 20 is associated with a different filter coefficient (i.e., each processing unit 20 is associated with two taps of the filter) and generates a corresponding product for each output value. In this manner, each processing unit 20 receives an

indication (via accumulation input lines 102) of an ongoing sum from the predecessor processing unit 20 (except for the first processing unit 20_n) in the chain 10, updates the ongoing sum with an additional product and furnishes an indication of the ongoing sum (via accumulation output lines 110) to the successor processing unit 20 (except for the last processing unit 20₀) in the chain 10.

Referring to Fig. 3, as an example, a particular processing unit 20_k receives three input signals that indicate three respective values: $p(k)$, the broadcast input value (from a broadcast input line 205) that is equivalent to some x value; $r(k+1)$, a delayed input value indicated by the predecessor processing unit 20_{k+1} (not shown) in the chain 10; and $q(k+1)$, an ongoing sum value indicated by the predecessor processing unit 20_{k+1} in the chain 10. The processing unit 20_k furnishes two output signals (to the successor processing unit 20_{k-1} (not shown)) that indicate two respective values: $r(k)$ and $q(k)$. Mathematically, $r(k)$ and $q(k)$ may be described by the following equations:

$$r(k) = r(k+1) \quad \text{Eq. (4)}$$

$$q(k) = q(k+1) + C(x) \cdot \{p(k) + r(k+1)\} \quad \text{Eq. (5)}$$

Based on the above-described principle of operation, it may be observed that $r(k+1)=x(i-j)$ when $p(k)=x(i+j)$, and thus, for these input values, $q(k) = C(j) \cdot [x(i+j)+x(i-j)]$.

Referring back to Fig. 2, as an example, in some embodiments, the processing units 20₀, 20₁, . . . , 20_k, . . . 20_{n-1}, 20_n are associated with the $C(n)$, $C(n-1)$, . . . $C(k)$, . . . $C(1)$, $C(0)$ coefficients, respectively, and the processing chain 10 begins with processing unit 20_n and ends with the processing unit 20₀. Thus, as an example, for a particular output value, the processing unit 20_n provides the first product (called the $C(0)$ product) by multiplying the $x(i)$ value by $C(0)$. It is noted that for $j=0$, $x(i+j)=x(i-j)=x(i)$. The product that is provided by the processing unit 20_n begins a sum to which all the processing units 20 contribute another product. In this manner, the processing unit 20_{n-1} receives signals from the processing unit 20 that indicate the $C(0) \cdot x(i)$ product. The processing unit 20_{n-1} adds the term $C(1) \cdot [x(i+1)+x(i-1)]$, called the $C(1)$ product, to the ongoing sum and furnishes signals to the next processing unit in the chain, etc. Eventually, the processing unit 20₀ adds the last product (the $C(N) \cdot [(x+N)+(x-N)]$ product) to the rolling sum to generate the signal at the output terminals 11. It is noted that when the processing chain 10 receives $x(0)$ to begin the filtering, $N+1$ clock cycles are consumed to produce the first valid output value. However, thereafter, the processing chain 10 produces an output on every

clock cycle, thereby resulting in 100% throughput.

Referring back to Fig. 3, as an example, in some embodiments, the processing unit 20k may include input 22 and output 24 registers that delay the digital signal that indicates each $r(k+1)$ value before communicating the signal to the successor processing unit 20k-1. In this manner, in some embodiments, the input register 22 receives the digital signal that indicates the $r(k)$ signal (via the input lines 104) on a positive edge (for example) of a processing clock signal (called CLK_1) and communicates the stored digital signal to the output register 24 on the next positive edge (as an example) of the CLK_1 signal. The output register 24 indicates (via the output lines 108) the stored digital signal (i.e., indicates the $r(k)$ value) to the successor input register 22 in the processing chain 10.

The processing unit 20k also includes an adder 32, a multiplier 34 and an adder 36 to generate the $q(k)$ value. In some embodiments, these components are clocked by a clock signal (called CLK_2) that is synchronized to the CLK_1 clock signal and has a frequency that is a multiple of the frequency of the CLK_1 clock signal so that the $q(k)$ signal is generated on each positive edge (for example) of the CLK_1 signal. In this manner, the adder 32 is coupled to receive the digital signal that indicates the $r(k+1)$ value synchronously with the reception of the $r(k+1)$ value by the input register 22. The adder 32 adds this digital signal with a digital signal that indicates the current $p(k)$ value to form an indication of $p(k) + r(k+1)$. The multiplier 34 multiplies the digital output signal from the adder 32 with a digital signal that indicates the associated filter coefficient to produce the digital signal that indicates the $C(k) \cdot [p(k) + r(k+1)]$ signal. The digital signal that indicates the filter coefficient is stored in a coefficient register 30. The coefficient may be changed via data and control lines 16 that are coupled to the register 30. The adder 36 combines the digital output signal from the multiplier 34 with the $q(k+1)$ signal to produce the digital output signal (on the output lines 110) that indicates the $q(k)$ value.

Fig. 4 depicts an example of the integration of the processing chain 10 and the tap selecting circuit 12 to form a selectable tap filter 199 that permits the selection of up to seven taps. In this manner, the filter 199 includes a processing chain of five processing units 20₀, 20₁, 20₂, 20₃ and 20₄. The filter 199 also includes four termination units 100₀, 100₁, 100₂, and 100₃ (of the same design 100) that are associated with the processing units 20₀, 20₁, 20₂, and 20₃, respectively. In this manner, a particular termination unit 100 may be selected (via the appropriate bit in a register 200) to terminate the processing chain at its associated processing

unit 20. For example, the termination unit 100₂ may be selected to terminate the processing chain at the processing unit 20₂ and thus, create a five tap processing chain. Similarly, the termination unit 100₁ may be selected to terminate the processing chain at the processing unit 20₁ and thus, create a three tap processing chain.

5 The selection of a particular termination unit 100 may be accomplished via selection lines 103, each of which extends to a different termination unit 100. In this manner, when a particular selection line 103 is asserted (driven high, for example) the associated termination unit 100 is selected and thus, the number of taps is selected. It is noted that only one selection line 103 is asserted, and the remaining selection lines 103 are deasserted (driven low, for example). The
10 selection lines 103 may indicate respective selection bits of a selection register 200, and the selection bits may be stored in the register 200 via data and control lines 201.

As depicted by the termination unit 100₂, each termination unit 100 may include a multiplexer 124 that selects either the broadcast input lines 205 (when the termination unit 100 is selected) or the output lines 108 (when the termination unit 100 is deselected) of the predecessor
15 processing unit 20 and couples the selected lines to the input lines 104. The termination unit 100 may also include another multiplexer 122 that selects either the output lines 110 (when the termination unit 100 is selected) of the previous processing unit 20 or the lines 118 (when the termination unit 100 is deselected) indicative of "0" (i.e., a zero sum) and couples the selected lines to the input lines 102.

20 Referring to Fig. 5, in some embodiments, the processing unit and termination unit may be combined to form a combined unit 300. In this manner, the unit 300 may be replicated to form a processing chain of an arbitrary length. This processing chain may be effectively truncated as needed to suit a particular filtering application, as described above.

25 While the invention has been disclosed with respect to a limited number of embodiments, those skilled in the art, having the benefit of this disclosure, will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations as fall within the true spirit and scope of the invention.

What is claimed is:

1 1. A digital signal processing circuit comprising:
2 a chain of processing units to receive indications of discrete input values, each processing
3 unit being associated with one of a group of filter coefficients; and
4 a tap selection circuit to select a group of the processing units of the chain to produce an
5 indication of a filtered discrete output value for each discrete input value.

1 2. The processing unit of claim 1, wherein the chain of processing units comprises a
2 systolic chain.

1 3. The processing circuit of claim 1, wherein the tap selection circuit selects a
2 number of taps of the processing circuit.

1 4. The processing circuit of claim 1, wherein the group of processing units
2 progressively accumulate a summed value to form each output value and the tap selection circuit
3 comprises:
4 a multiplexer to designate a point in the chain at which the accumulation begins.

1 5. The processing circuit of claim 4, wherein each processing circuit comprises a
2 first input terminal to receive the indications of the discrete input values from a processing circuit
3 input line common to the processing circuits and a second input terminal to receive the
4 indications of the discrete input values from another processing circuit, the multiplexer coupling
5 the first and second terminals of one of the processing circuits together to designate the point in
6 the chain at which the accumulation begins.

6. The processing circuit of claim 1, wherein each processing circuit comprises:
a first adder circuit to generate an indication of a summation of two of the discrete input values; and
a multiplier circuit coupled to the first adder circuit to generate an indication of a product of a coefficient associated with said each processing circuit and the summation of the two discrete values.

7. The processing circuit of claim 6, further comprising:
a second adder circuit coupled to the first multiplier circuit to combine the summation of the two discrete input values with a progressive summation provided by another processing circuit.

8. The processing circuit of claim 7, wherein the tap selection circuit comprises:
a multiplexer to selectively furnish an indication of a zero to the second adder circuit of one of the processing units to designate a point where the progressive sum begins.

9. The processing circuit of claim 1, wherein the tap selection circuit comprises:
a register storing bits indicative of the processing units in the group.

10. The processing circuit of claim 1, wherein each processing unit comprises:
a register storing the indication of the associated filter coefficient.

11. The processing circuit of claim 1, wherein the processing circuit comprises a finite impulse response filter.

12. The processing circuit of claim 1, wherein the processing circuit comprises an infinite impulse response filter.

1 13. A digital signal processing circuit comprising:
2 a processing chain having a selectable number of taps; and
3 a tap selection circuit coupled to the processing chain to selectively establish the number
4 of taps of the chain.

1 14. The processing circuit of claim 13, wherein the tap selection circuit comprises:
2 a multiplexer to select one of the taps as the beginning tap in the chain.

1 15. The processing circuit of claim 14, wherein the multiplexer sets a cumulative sum
2 at the selected tap to zero.

1 16. The processing circuit of claim 14, wherein the multiplexer sets a delay at the
2 selected tap to zero.

1 17. The processing circuit of claim 13, wherein the tap selection circuit comprises:
2 a register storing bits indicative of the number of taps.

1 18. The processing circuit of claim 13, wherein the tapped delay line comprises:
2 registers storing indications of filter coefficients associated with the taps.

1 19. The processing circuit of claim 13, wherein the processing circuit comprises a
2 finite impulse response filter.

1 20. The processing circuit of claim 13, wherein the processing circuit comprises an
2 infinite impulse response filter.

1 21. A method comprising:
2 providing a processing chain line having a fixed number of taps;
3 disabling some of the taps of the chain; and
4 using the remaining taps to establish a finite impulse response filter.

1 22. The method of claim 21, wherein the disabling comprises:
2 selecting one of the taps as the beginning tap in the delay line.

1 23. The method of claim 21, wherein the disabling comprises:
2 setting a cumulative sum at one of the taps to zero.

1 24. The method of claim 21, further comprising:
2 storing bits indicative of the number of remaining taps.

1 25. The method of claim 21, further comprising:
2 storing rewritable indications of filter coefficients associated with the taps.

DISCRETE FILTER

ABSTRACT OF THE DISCLOSURE

A digital signal processing circuit includes a chain of processing units having a selectable number of taps and a tap selection circuit. The tap selection circuit is coupled to the chain of processing units to establish the number of taps of the chains.

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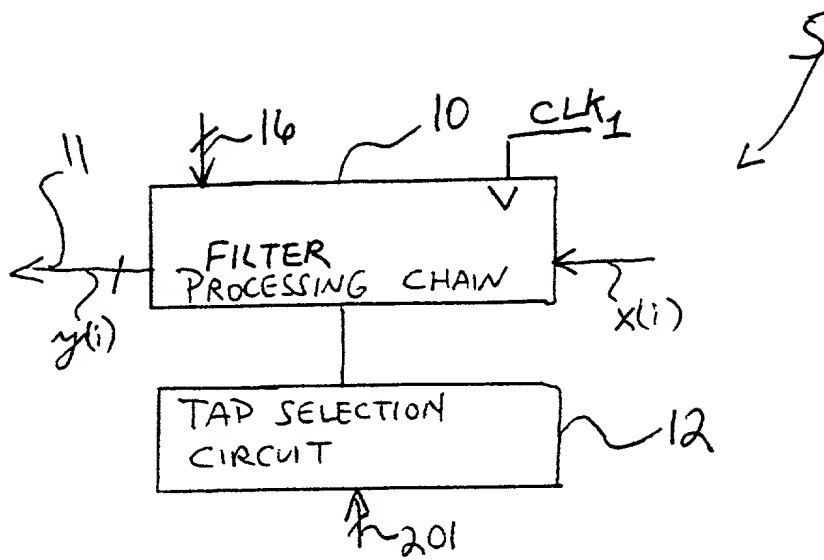


FIG. 1

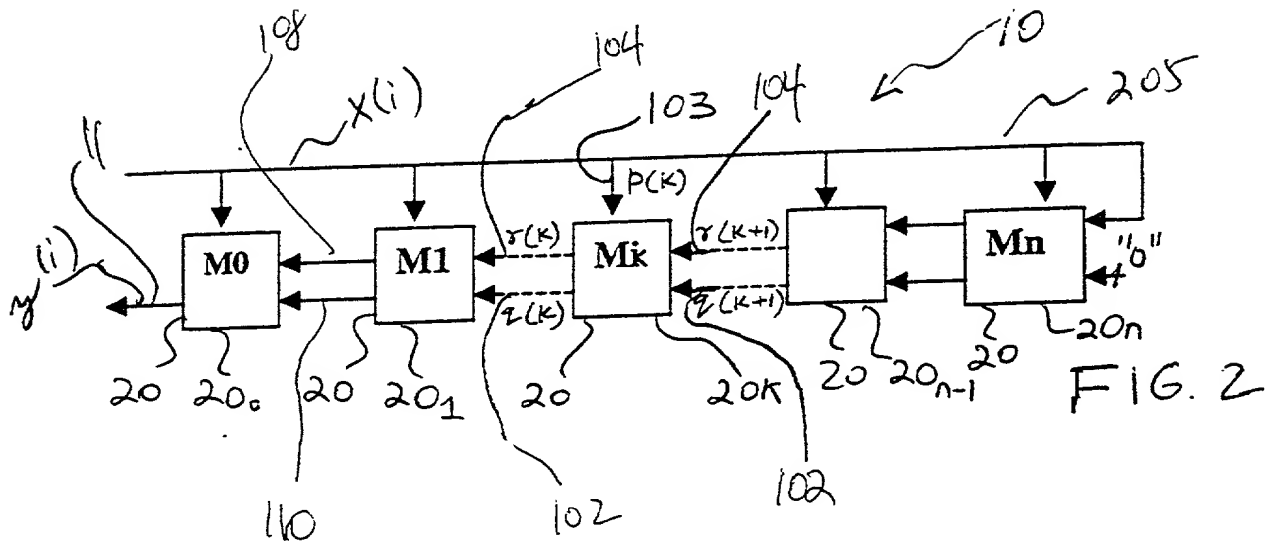


FIG. 2

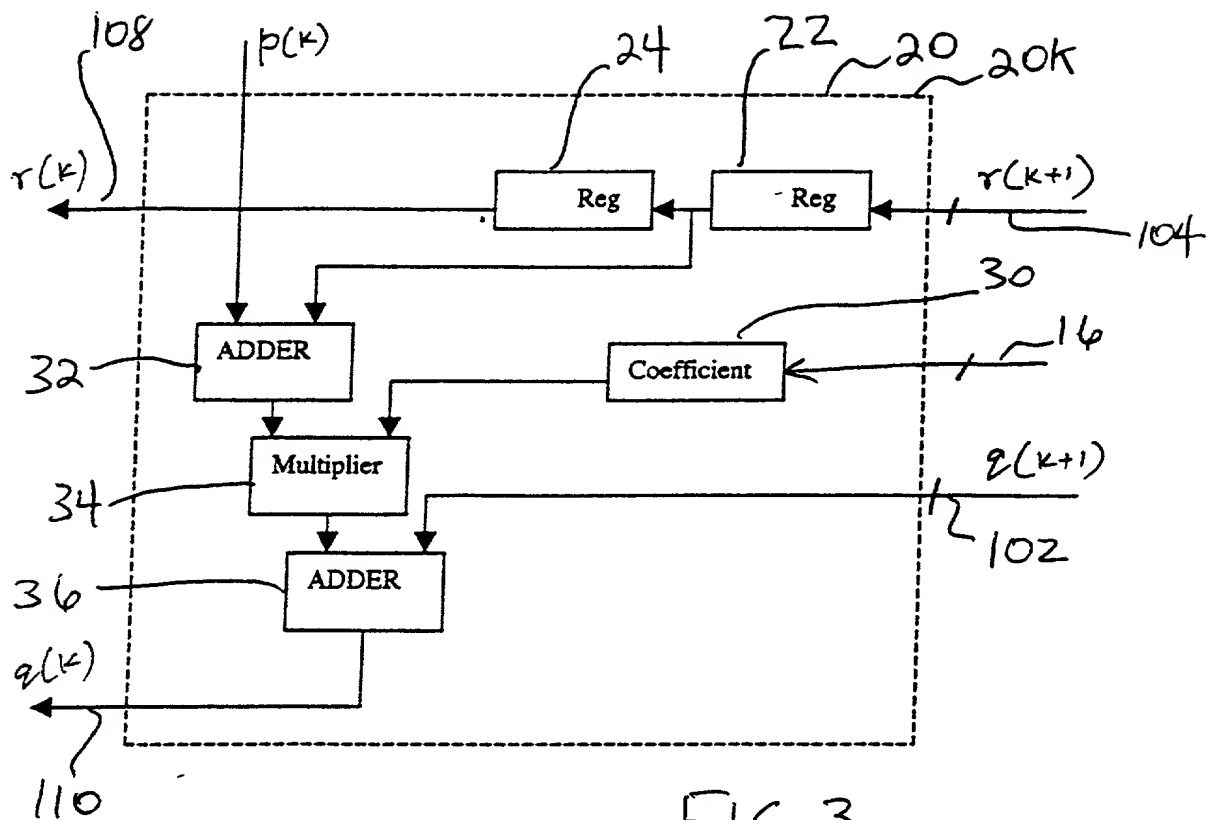


FIG. 3

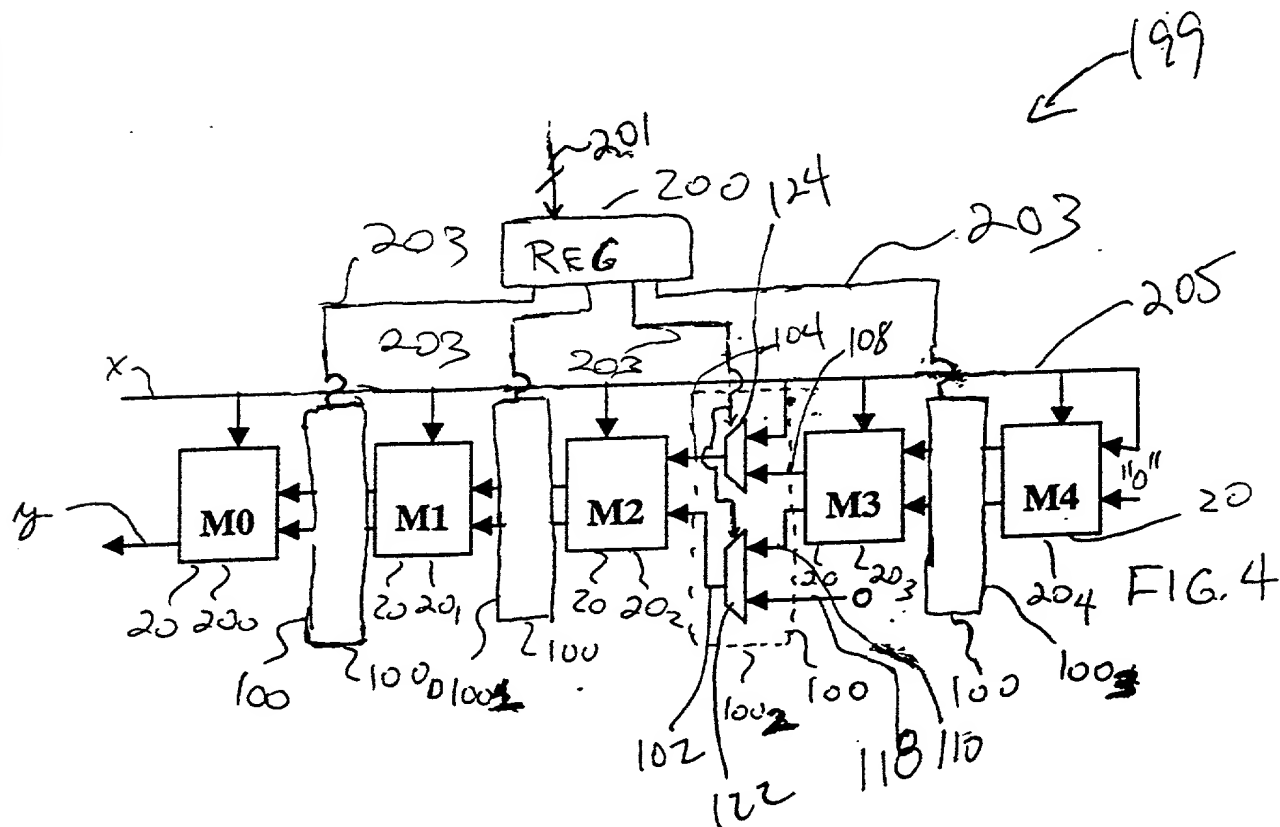
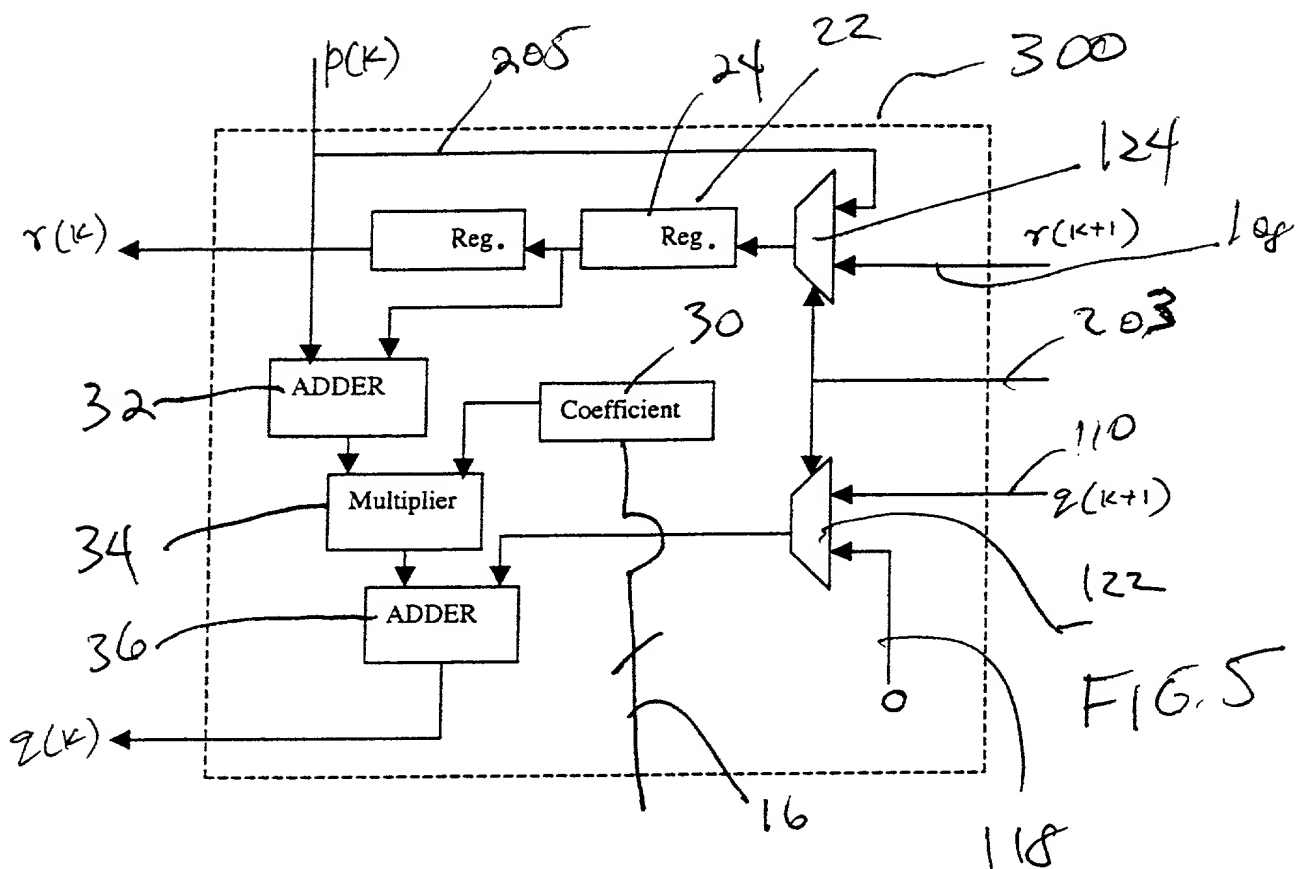


FIG. 4



DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below, next to my name.

I believe I am the original, first, and sole inventor (if only one name is listed below) or an original, first, and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

DISCRETE FILTER

the specification of which

X	is attached hereto.
	was filed on _____ as
	United States Application Number _____
	or PCT International Application Number _____
	and was amended on _____
	(if applicable)

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claim(s), as amended by any amendment referred to above. I do not know and do not believe that the claimed invention was ever known or used in the United States of America before my invention thereof, or patented or described in any printed publication in any country before my invention thereof or more than one year prior to this application, that the same was not in public use or on sale in the United States of America more than one year prior to this application, and that the invention has not been patented or made the subject of an inventor's certificate issued before the date of this application in any country foreign to the United States of America on an application filed by me or my legal representatives or assigns more than twelve months (for a utility patent application) or six months (for a design patent application) prior to this application.

I acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal Regulations, Section 1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119(a)-(d), of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s):			Priority Claimed	
Number	(Country)	(Day/Month/Year Filed)	Yes	No
Number	(Country)	(Day/Month/Year Filed)	Yes	No
Number	(Country)	(Day/Month/Year Filed)	Yes	No

I hereby claim the benefit under title 35, United States Code, Section 119(e) of the United States provisional application(s) listed below:

_____ (Application Number)	_____ (Filing Date)
_____ (Application Number)	_____ (Filing Date)

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose all information known to me to be material to patentability as defined in Title 37, Code of Federal regulations, Section 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application:

_____ (Application Number)	_____ Filing Date	_____ (Status-patented, pending, abandoned)
_____ (Application Number)	_____ Filing Date	_____ (Status-patented, pending, abandoned)

I hereby appoint Timothy N. Trop, Reg. No. 28,994; Fred G. Pruner, Jr., Reg. No. 40,779, Dan C. Hu, Reg. No. 40,025; Coe F. Miles, Reg. No. 38,559, and John R. Merklings, Reg. No. 31,716 my patent attorneys, of TROP, PRUNER, HU & MILES, P.C., with offices located at 8554 Katy Freeway, Ste. 100, Houston, TX 77024, telephone (713) 468-8880, and Joseph R. Bond, Reg. No. 36,458; Richard C. Calderwood, Reg. No. 35,468; Sean Fitzgerald, Reg. No. 32,027; David J. Kaplan, Reg. No. 41,105; Leo V. Novakoski, Reg. No. 37,198; Naomi Obinata, Reg. No. 39,320; Thomas C. Reynolds, Reg. No. 32,488; Steven P. Skabrat, Reg. No. 36,279; Howard A. Skaist, Reg. No. 36,008; Steven C. Stewart, Reg. No. 33,555; Raymond J. Werner, Reg. No. 34,752; and Charles K. Young, Reg. No. 39,425; my patent attorneys, of INTEL CORPORATION; with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected herewith.

Send correspondence to Timothy N. Trop, TROP, PRUNER, HU & MILES, P.C., 8554 Katy Freeway, Ste. 100, Houston, TX 77024 and direct telephone calls to Fred G. Pruner, Jr., (713) 468-8880.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full Name of Sole/First Inventor:
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Inventor's Signature:

Tinku Acharya

Date:

1/6/99

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